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Tilt Rotor Aircraft Modeling Using a Generic Simulation Structure

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Abstract

Rapid ongoing and projected changes in the defense economy imply that today's tendency to use a wide variety of modeling simulation structures may not be affordable tomorrow. Today's complex aircraft and related systems require highly sophisticated mathematical models to support specific test applications. The past can be characterized as a time when many new aircraft were developed with the associated funding to develop one or more unique simulation models for each new aircraft. The future points to fewer new aircraft and reduced defense budgets, placing more emphasis on generic models, including reconfigurable simulation model structures. Complexity requirements for modeling and simulation tomorrow will increase with highly specialized mission applications and the requirement to participate in multi-service distributed interactive simulation scenarios. This paper discusses the use of a generic simulation model structure to rapidly model and analyze an isolated rotor system for a state-of-the-art tilt rotor aircraft.

Background

The future points to fewer, more complex and costly aircraft, designed for multi-mission tasks. Current and past helicopters or rotorcraft have been restricted primarily to hover and low speed tasks, and tasks requiring forward speeds less than 200 kt. Modern tilt rotor aircraft are designed both for hover and low speed tasks, and also for forward flight scenarios requiring speeds well in excess of 200 kt. Factors like hover figure of merit, propulsive efficiency, and rotor blade loading influence tiltrotor aircraft rotor design. As discussed in reference 1 and summarized in Table 1, the multi-service V-22 tiltrotor aircraft rotor design parameters included the diameter, number of blades, tip speed, airfoil, twist, chord, taper ratio, and spinner configuration.

Rotorcraft rotor system configurations available today include single main rotor/tail rotors, tandem rotors, inter-meshing rotors, tilt rotors, and co-axial rotors. The possible real time simulation model complexity variations include elastic blade element models, rigid blade element models, rotormap models, Bailey rotor models, full degree-of-freedom (DOF) linear models, and lower order DOF linear models. Selectable rotor inflow modules and selectable rotor airload modules may also be needed for tomorrow's rotorcraft simulation applications. Current rotorcraft real time simulators typically feature high fidelity cockpits, and have air vehicle models that can be used for basic pilot familiarization and training, but not for supporting many flight test scenarios. These trainers may have rotormap rotor models that treat the rotor system as a disk, rather than modeling the individual blades. The rotormap models may be computationally efficient, but as noted in reference 2, may be inaccurate for large changes in density altitude, high speed flight, autorotation, and aggressive maneuvers. Today the complexity of deriving a real time blade element tilt rotor aircraft rotor model from basics can be a very challenging task. Tomorrow's generic simulation model structures, with graphical user interfaces, will be able to greatly simplify the task of developing blade element rotor models. Unachieved simulation goals today, such as real-time rotorcraft component vibratory load prediction, should be achievable tomorrow. Once component vibratory loads can be predicted in real time using easily reconfigurable generic model structures, simulation becomes a true flight test support tool.

Generic Model Structure

A generic simulation model structure starts with a top down view of the simulation scenario. This means that the initial vision or view identifies the complete rotorcraft. From this view, it is possible to identify major aircraft components like the main rotor(s), fuselage, tail rotor, and landing gear. Using imaginary X-ray vision, it is also possible to identify the engines, drive systems, control systems,

avionic and other systems. The level of aircraft system detail continues to the individual component.

Model Tree. An example of a generic simulation model structure tree is presented in figure 1. Note that the major components or supercomponents presented include the environment, rotors 1 & 2, wing, propulsion, airframe, flight controls, and aerodynamic interference. From a top-down approach, the rotorcraft consists of a complete unit composed of group of supercomponents. From a bottoms-up approach, we see a group of supercomponents, which can be reconfigured to produce specified rotorcraft. This implies that if supercomponents were available for a variety of rotorcraft, it would be relatively easy to reconfigure the simulation model to represent other aircraft.

Model Complexity Levels. Tomorrow's simulation models will be required to support a variety of tasks with varying levels of complexity. Using the highest fidelity model available for simulation support which could be done with basic linear models, does not optimize computational resources. Trying to use linear models for defining high speed edge-of-the-envelope limits may produce questionable results. The model complexity should be compatible with the tasks to be supported. Figure 2 shows representative levels of complexity selectible with a generic simulation model structure rotor system.

V-22 Aircraft

The V-22 is a Bell/Boeing tilt rotor aircraft currently being evaluated by an integrated contractor and government test team at the Naval Air Warfare Center Aircraft Division at Patuxent River, MD. The V-22 has a triple redundant fly-by-wire digital primary flight control system and an automatic flight control system. The aircraft features two three-bladed rotors with nacelles that tilt from 97 deg (helicopter mode) to zero deg (airplane mode). Developing a real time simulation model of the complete V-22 rotorcraft represents a very challenging task. Currently, the real time V-22 models at Patuxent River, Bell, and Boeing employ rotor disk models. A real time V-22 blade element rotor model has the potential to enhance test and training applications by predicting blade loads due to flight condition or external disturbances.

V-22 Rotor Model. The concept of using a generic simulation model structure to rapidly model a complex helicopter rotor system needs to be demonstrated. The V-22 tilt rotor aircraft is a good candidate, since it features two main rotors that tilt, plus, blades with five airfoil segments, that have a high degree of twist and taper. This demonstration work involved developing a blade element V-22 isolated rotor system using a generic simulation model structure. The work was sponsored by the US Navy-American Society for Engineering Education (ASEE) Summer Faculty Research Program. An assistant professor (electrical engineer) from the Fort Valley State College in Fort Valley, GA., worked on developing a V-22 rotor model at the Naval Air Warfare Center Aircraft Division Patuxent River MD., during the summer of 1995. The work was performed in less than a month, with most of the time spent learning about the generic simulation model structure and locating input data. A future goal is to be able to develop and validate a complex rotor model in one day using a generic simulation model structure. The following paragraphs discuss V-22 rotor model input data, data sources, model testing and validation.

Model Input Data. Basic geometrical data are required to develop a model using a reconfigurable structure. In this case the required input data field and associated units are specified. Most of the required model input data comes from the original aircraft manufacturer, simulator developer, related research or test report or database associated with the aircraft. There are no standard overall model development databases.

Data Sources. The V-22 rotors contain four airfoil sections, plus

the blade cuff, for a total of five airfoil sections to model the blade. Basic airfoil data were obtained from the Carderock Division of the Naval Surface Warfare Center. These airfoil data were read directly into the generic simulation model. The model rotor mass, twist, and chord distribution, as a function of non-dimensional radius, are presented in figure 3. This blade model information shows good agreement with the V-22 design data in reference 1.

Isolated Rotor Test

It will be important to validate each component in tomorrow's reconfigurable simulation models. A generic simulation structure provides easy access to each modeling component, but today, standard validation criteria do not exist at the rotorcraft component level. The most important component for a helicopter is the main rotor, but often little isolated rotor test data are available.

Performance - Helicopter Mode. Isolated rotor hover performance model data are presented in figures 4 and 5. Figure 4 shows that the predicted rotor hub thrust increases linearly with swashplate collective pitch for angles up to approximately 9 degrees. Figure 5 shows the classical non-dimensional hover performance in terms of power coefficient versus thrust coefficient. Note that the power required increases slightly from a uniform inflow model to a general finite state inflow model.

Stability - Helicopter Mode. Isolated rotor stability in hover can be discussed in terms of the rotor eigenvalues or characteristic roots. Figure 6 shows the eigenvalues for the V-22 blade element model in hover. All blade roots are stable. The rotor flap modes are shown by the complex roots, and the inflow root is shown on the real axis.

Stability - Airplane Mode. The V-22 isolated rotor system can be flown in a virtual wind tunnel mode to evaluate its stability. Figure 7 shows the isolated blade eigenvalues for the airplane mode. Note that all roots are stable. Again, the rotor flap modes are shown by the complex roots, and the inflow root is shown on the real axis.

Model Validation.

Model validation is relatively straight forward for the total aircraft, provided adequate flight test data are available. If the total model response does not match flight test data, the validity of each supercomponent must be checked. Flight test data for components like an isolated main rotor may be difficult to obtain. This means that whirl tower and wind tunnel may be the only source of quantitative data, and this data may be for scaled models. Isolated rotor validation data for the V-22 were not available for this study.

Summary

Today's tendency to use a wide variety of simulation models may not be affordable tomorrow. Generic structure simulation programs offer the potential for enhancing model development and application. This paper reviews the development and application of a V-22 blade element isolated rotor system using a generic model structure. The basic model rotor system performance and stability characteristics are examined. Standard simulation air vehicle databases and standard isolated component validation techniques could be used to enhance model development and check-out. Data were not available to completely validate the isolated rotor model. The generic blade element rotor model could be expanded to include the fuselage, wing, and tail surfaces. A generic rotorcraft simulation structure offers the potential to enhance future reconfigurable simulation applications.

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2. Choi, K., DuVal, R., and He, CJ., "Helicopter Rotor Disk and Blade Element Comparisons," ART Report No. 1002, October 12, 1995.

Table 1
V-22 Rotor Design Criteria
(from reference 1)

Parameter	Selection	Criteria
Diameter	38 ft	LHA ship operations
Number of Blades	3	Folding requirement, blade dynamic response
Tipspeed	Hover 790 fps Cruise 662 fps	Performance, Sound Best performance tradeoff
Airfoils	XN-28 XN-18 XN-12 XN09 BladeCuff	Optimize performance in hover, cruise and low speed maneuver
Twist	47.9 deg Nonlinear	Best hover/cruise tradeoff
Chord	Ce = 2.089 ft	Best Hover/cruise tradeoff, g capability at 60 kt
Taper Ratio	.637	Best hover performance constrained by folding requirement

- Rotorcraft
  - Environment
  - Rotor 1
  - Rotor 2
  - Wing
  - Propulsion
  - Airframe
  - Flight Controls
  - Aerodynamic Interference

Figure 1
Generic Simulation Structure
Compressed Model Tree Diagram

- Rotor
  - Bailey Rotor
  - Rotor Map
  - Blade Element
    - Hub
      - Articulated
        - Linear damper
        - Non-linear damper
      - Bearingless
      - Hingeless
      - Teetering
      - Gimbal
    - Blade
      - Rigid
      - Elastic
    - Airloads
      - Analytic Linear Unsteady
      - Quasi Steady
      - Quasi Unsteady
      - Dynamic Stall
    - Induced Velocity
      - Uniform Inflow
      - Three State Inflow
      - Six State Inflow
      - Prescribed Vortex
      - Free Vortex

Figure 2
Rotor Model Levels of Complexity

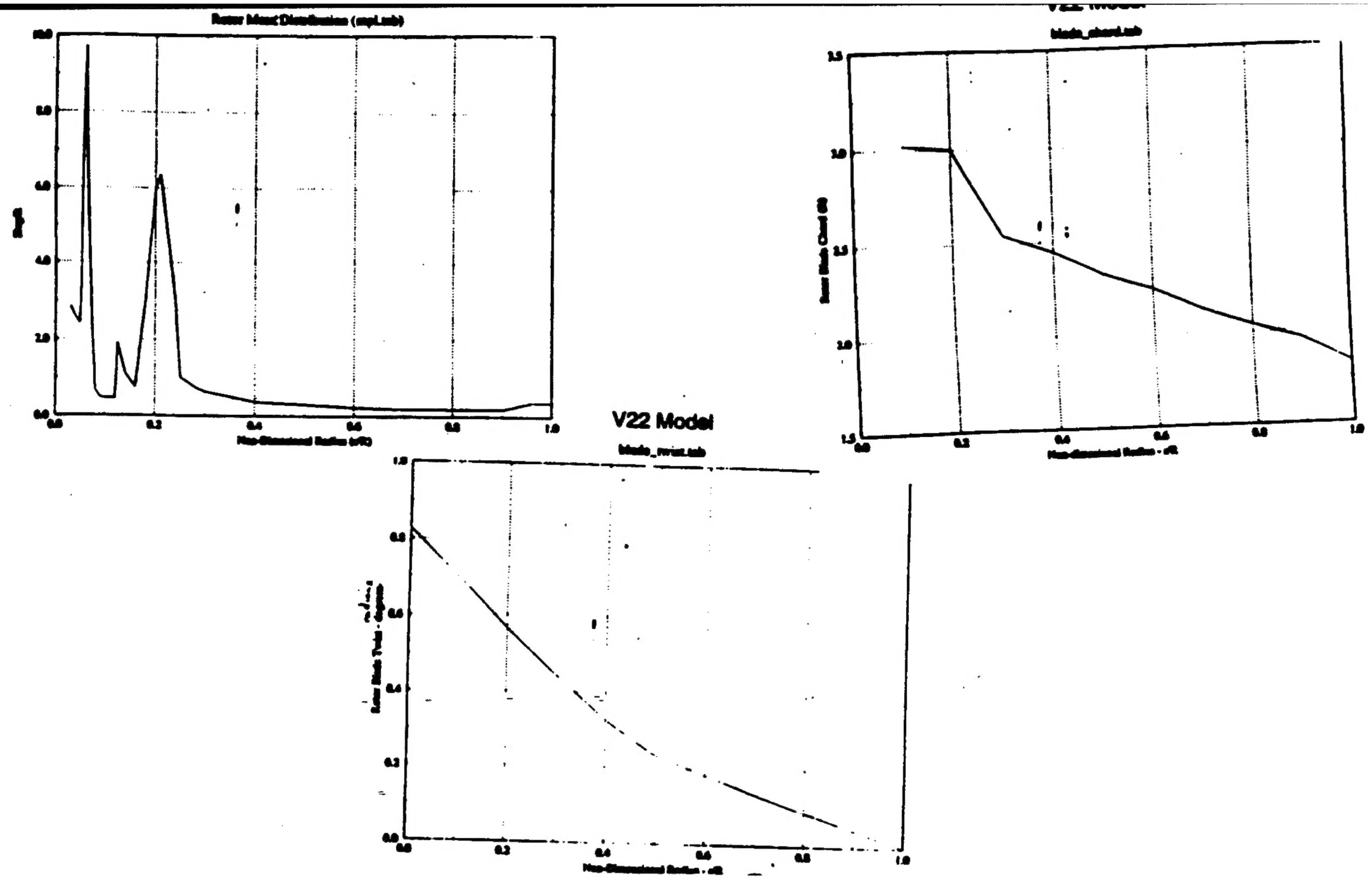

Figure 3
Rotor Blade Mass, Twist, and Chord Distribution

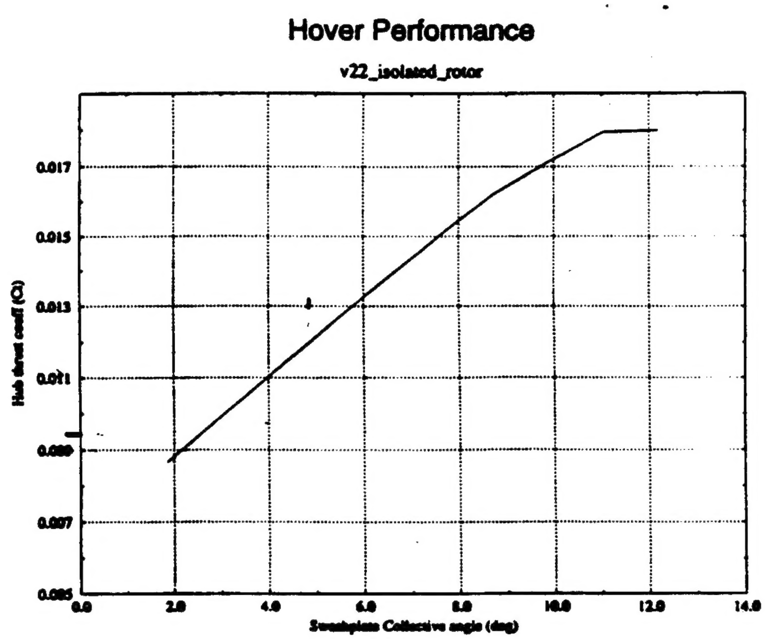

Figure 4
Hover Performance - Hub Thrust

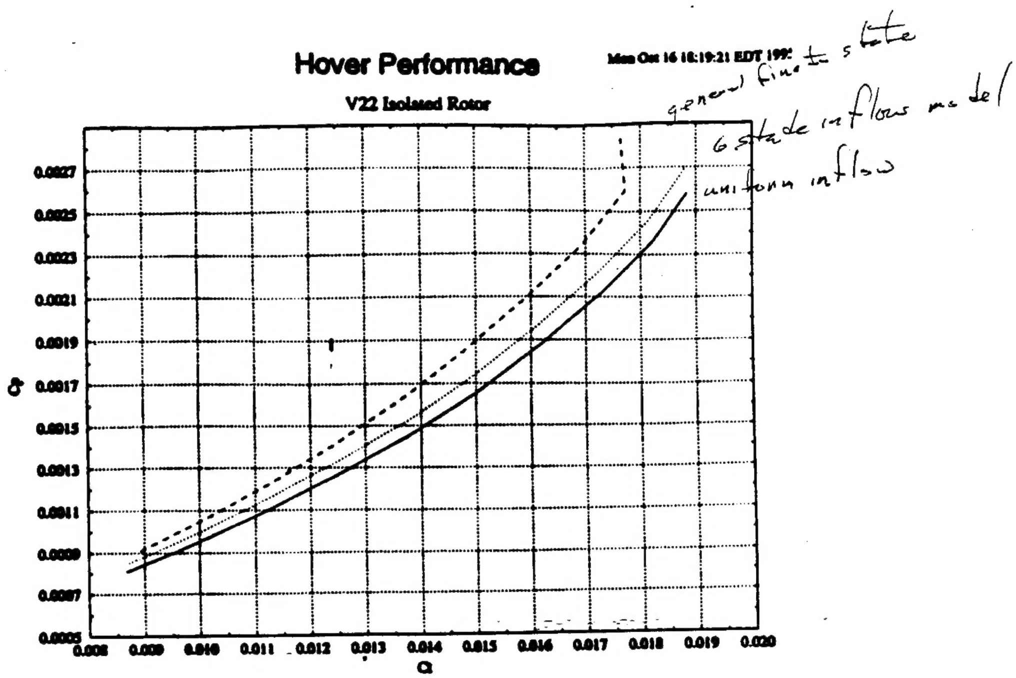

Figure 5
Hover Performance

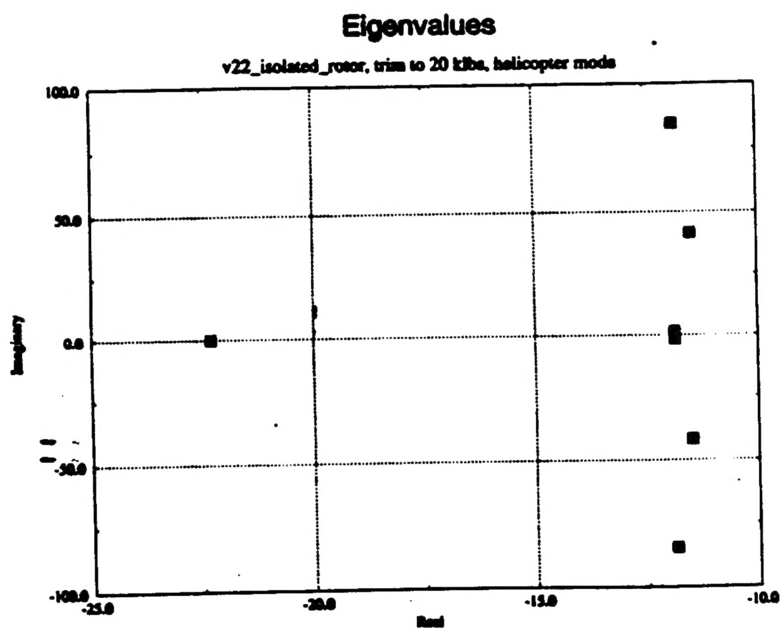

Figure 6
Rotor Stability in Hover

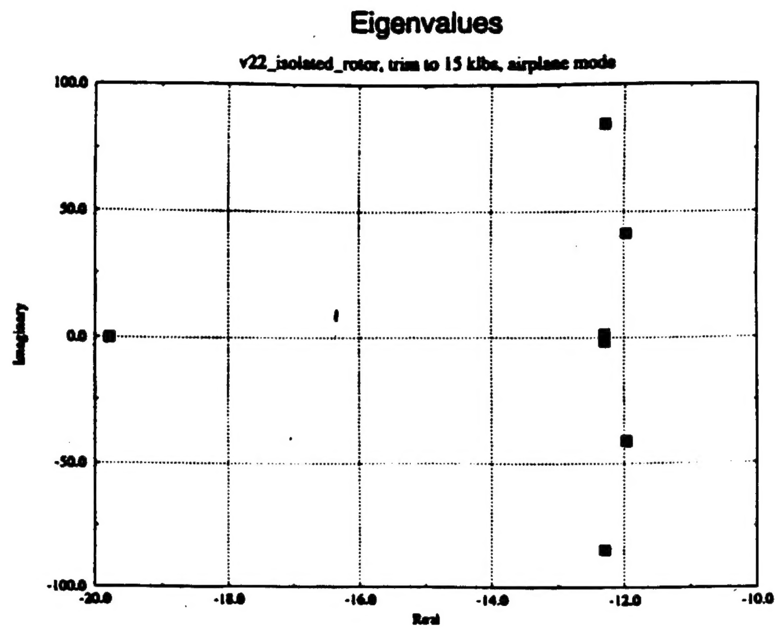

Figure 7
Rotor Stability in Airplane Mode